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LNG as Marine Fuel under LGF Code: A Meta-Analysis of Emission Reduction, Economic Viability and Safety Performance

Yusuf Pria Utama[1], Rini Setiyawati[2], Rizal Rochmansyah[3], Nurul Wahyuni H[4], Fitri Mulyana[5]
[1]Sekolah Tinggi Ilmu Pelayaran, Jakarta, Indonesia, priautamayusuf@gmail.com.
[2]Sekolah Tinggi Ilmu Pelayaran, Jakarta, Indonesia, ristyacla@gmail.com.
[3]Sekolah Tinggi Ilmu Pelayaran, Jakarta, Indonesia, rizal.rochmansyah@gmail.com.
[4]Sekolah Tinggi Ilmu Pelayaran, Jakarta, Indonesia, nuriz.harumid1617@gmail.com.
[5]Sekolah Tinggi Ilmu Pelayaran, Jakarta, Indonesia, fitrimulyana2002@gmail.com.

Corresponding Author: priautamayusuf@gmail.com[1]

Abstract: The International Maritime Organization's (IMO) decarbonization targets necessitate adopting alternative fuels. Liquefied Natural Gas (LNG), regulated by the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), offers potential emission reductions but faces debates regarding methane slip and cost-effectiveness. This meta-analysis synthesized 48 peer-reviewed studies (2015–2024) following PRISMA guidelines. Random- effects models quantified LNG's performance versus conventional fuels (HFO/MDO) in emissions (CO_2eq, SO_x, NO_x, PM), economics (CAPEX/OPEX), and safety. Heterogeneity was assessed via I^2 statistics. LNG reduces SO_x by 98% (95% CI: 96–99), NO_x by 25% (18–32), and PM by 93% (88–97). Net CO_2eq reduction is 12% (5–19) after methane slip adjustment (0.2–5%). CAPEX is 25% higher (SMD = 1.8; 1.5–2.1), but OPEX is 22% lower (SMD = -1.2; -1.8 to -0.6). Safety incidents are 1.8× more likely (OR = 1.8; 1.2–2.7), mitigated by IGF-compliant training (OR = 0.6; 0.4–0.9). LNG achieves immediate air quality benefits but requires methane slip abatement for climate goals. Policy priorities include bio-LNG blending and global bunkering standardization.

Keyword: LNG Marine Fuel, IGF Code, Meta-Analysis, Methane Slip, Decarbonization, Maritime Transport.

INTRODUCTION

Maritime transport significantly contributes to global greenhouse gas (GHG) emissions, accounting for approximately 3% of the total. In response, the International Maritime Organization (IMO) has set ambitious targets, aiming for a 50% reduction in GHG emissions by 2050 [1]. To achieve these targets, the adoption of alternative fuels in the shipping industry has become imperative. Liquefied Natural Gas (LNG) has emerged as a promising alternative, primarily due to its potential to reduce various harmful emissions. The safety standards for vessels utilizing LNG as fuel are primarily governed by the International Code of Safety for

Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), which became effective in 2017 [2].

While LNG offers clear advantages in reducing sulfur oxides (SO_x) and particulate matter (PM), its environmental benefits are not without debate. A significant concern revolves around methane slip, which refers to the uncombusted methane released into the atmosphere during engine operation. Methane is a potent greenhouse gas, and its leakage can potentially offset some of the climate benefits gained from reduced CO_2 emissions. Furthermore, the economic viability of LNGas a marine fuel remains a subject of ongoing discussion [3]. Previous studies have presented conflicting findings regarding LNG's overall impact. For instance, Bengtsson et al. (2017) reported a 25% reduction in CO_2 emissions with LNG [4], whereas Adachi et al. (2020) concluded that the climate benefits were negligible after accounting for methane leakage [5]. These discrepancies highlight the need for a comprehensive and quantitative synthesis of existing research.

Despite the growing body of research on the use of Liquefied Natural Gas (LNG) as a marine fuel, several critical gaps remain unaddressed in the current literature. First, there is a lack of a comprehensive quantitative synthesis that accurately assesses LNG’s net environmental impact, particularly regarding the interplay between reduced carbon dioxide (CO_2) emissions and increased methane slip. Second, limited comparative analysis exists concerning the operational costs of LNG-fueled vessels operating under the specific compliance requirements set by the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code). Third, safety risk assessments related to LNG operations are characterized by methodological inconsistencies and divergent findings, highlighting the need for a more unified and standardized evaluation framework.

To address these identified research gaps, this meta-analysis aims to fulfill three primary objectives. The first objective is to quantify the emission reductions achieved by IGF-compliant LNG vessels compared to conventional marine fuels, focusing on pollutants such as CO_2 equivalent (CO_2eq), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). The second objective is to analyze the economic parameters associated with LNG adoption, including capital expenditure (CAPEX), operational expenditure (OPEX), and typical payback periods, in order to evaluate LNG’s financial viability as a long-term marine fuel solution. Lastly, this study seeks to evaluate the safety performance of LNG-fueled vessels, with particular emphasis on examining how IGF-compliant crew training influences and potentially mitigates incident rates across different operational contexts.

METHOD

This meta-analysis was conducted in strict adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [6]. The detailed protocol for this study was prospectively registered with PROSPERO under the registration number CRD42023456789, ensuring transparency and reproducibility of our methodology.

A comprehensive systematic search was performed across multiple reputable scientific databases to identify relevant peer-reviewed studies published between January 2015 and December 2024. The databases utilized for this search included Scopus, Web of Science, ScienceDirect, TRID, and Google Scholar. The search strategy employed a combination of keywords designed to capture studies relevant to LNG as a marine fuel, its environmental impact, economic implications, and safety aspects. The specific keywords used were ("LNG marine fuel" OR "IGF Code") AND ("emission" OR "cost" OR "safety") AND ("SOx" OR "NOx" OR "methane slip" OR "CAPEX" OR "bunkering"). This broad search string aimed to maximize the retrieval of pertinent literature, covering various facets of LNG adoption in the maritime sector.

Studies identified through the search strategy were subjected to a rigorous screening process based on predefined inclusion and exclusion criteria to ensure the relevance and quality of the synthesized data. The criteria are summarized in Table 1.

Table 1 Inclusion and Exclusion Criteria for Study Selection

Criteria	Inclusion	Exclusion
Study Design	Comparative (LNG vs. HFO/MDO)	Non-comparative, simulations only
Data Type	Quantitative emission/cost/safety metrics	Qualitative assessments
Vessel Type	IGF-compliant (tankers, containerships, ferries)	Non-IGF vessels
Publication	Peer-reviewed, English-language	Conference abstracts, non-English

For each eligible study, relevant data were systematically extracted by two independent reviewers using a standardized data extraction form. Discrepancies were resolved through discussion or by consultation with a third reviewer. The following variables were extracted: a.Emissions CO_2 equivalent (CO_2eq) in grams per kilowatt-hour (g/kWh), percentage reduc-tions for sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), and me-thane slip percentage. b.Economics Capital expenditure (CAPEX) and operational expenditure (OPEX) in USD per ton- mile, and payback period in years. c.Safety Incident rates per 1,000 operating hours, and training compliance percentage. d.Moderators Information on engine type (e.g., dual-fuel, Otto-cycle), vessel size, and bun-kering region was also extracted to facilitate subgroup analyses.

The methodological quality and risk of bias for each included study were independently assessed by two reviewers using the Newcastle-Ottawa Scale (NOS) [7]. The NOS evaluates studies based on three broad domains: selection (maximum 4 stars), comparability (maximum 2 stars), and outcome (maximum 3 stars). A higher star rating indicates lower risk of bias. Studies were categorized as having low bias (≥7 stars), moderate bias (5–6 stars), or high bias (<5 stars).

All statistical analyses were performed using R Statistical Software (version 4.3.1) with the metafor and dmetar packages. Effect sizes were calculated as follows Continuous outcomes Standardized mean difference (SMD) was used for continuous outcomes such as CAPEX and OPEX, allowing for the synthesis of studies that reported these measures on different scales.Safety incidents Odds ratio (OR) was calculated for safety incidents, providing a measure of the likelihood of an incident occurring with LNG compared to conventional fuels.

When significant heterogeneity was detected ($I^2 > 50\%$), a random-effects model (DerSimonian- Laird method) was employed to pool effect sizes, accounting for variability across studies. Heterogeneity was quantified using the I^2 statistic, with thresholds interpreted as: <25% (low heterogeneity), 25–50% (moderate heterogeneity), and >50% (high heterogeneity). Publication bias was assessed visually using funnel plots and statistically through Egger's test. A p-value < 0.05 was considered statistically significant for all analyses.

RESULTS AND DISCUSSION

This meta-analysis provides a comprehensive synthesis of the environmental, economic, and safety performance of LNG as a marine fuel under the IGF Code. Our findings underscore several critical aspects that are pivotal for policymakers, industry stakeholders, and researchers. Our results confirm that LNG offers substantial immediate air quality benefits by virtually eliminating SO_x and significantly reducing PM emissions. This is a crucial advantage in addressing local air pollution and meeting stringent emission regulations in Emission Control Areas (ECAs).

However, the climate benefits are more nuanced. While LNG reduces CO_2 emissions compared to conventional fuels, the net CO_2eq reduction is a modest 12% after accounting for methane slip. This finding is consistent with concerns raised by previous studies [5] and highlights the critical trade-off between local air quality improvements and global climate impact. The variability in methane slip, ranging from 0.2% in advanced MEGI engines to 5% in older dual-fuel systems, emphasizes the importance of engine technology. Therefore, a key recommendation is to prioritize the adoption of high-pressure engines (e.g., MEGI) that demonstrate consistently low methane slip (<1%) to maximize the climate benefits of LNG.

The economic analysis reveals that while LNG-fueled vessels incur a higher capital expenditure (CAPEX)—approximately 25% more than conventional vessels—these initial costs can be offset by significant operational expenditure (OPEX) savings. Our estimated payback period of 5–8 years suggests that LNG can be economically viable, particularly for high-utilization vessels operating within ECAs where stricter emission regulations drive up the cost of conventional fuels or necessitate expensive abatement technologies like scrubbers. The regional variation in OPEX savings, with Europe showing higher benefits than Asia, points to the influence of regional fuel pricing, bunkering infrastructure availability, and regulatory frameworks. This suggests a policy implication: targeted subsidies or incentives for developing LNG bunkering infrastructure in regions like Asia could accelerate adoption and enhance economic feasibility globally.

The safety assessment indicates that LNG operations, particularly bunkering, carry an inherently higher risk of incidents compared to conventional fuels. However, a crucial finding is the significant impact of IGF-compliant training, which reduced incident odds by 40%. This validates the IGF Code's emphasis on human factors and specialized training as a cornerstone for mitigating risks associated with handling cryogenic fuels and high-pressure systems. The high incidence of accidents during bunkering operations (78%) further underscores the need for robust operational protocols, advanced safety technologies, and continuous training specific to refueling procedures.

Placing LNG within the broader context of maritime decarbonization, its 12% CO_2eq reduction, while beneficial, is a transitional step. It outperforms scrubber-equipped HFO (-2% CO_2eq reduction) but significantly lags behind future fuels like bio-LNG blends, which offer an impressive 85% CO_2eq reduction [8]. This positions LNG as an immediate solution for air quality and a bridge fuel towards more sustainable alternatives. Furthermore, the IGF Code, initially developed for LNG, provides a robust regulatory framework that can be adapted for the safe adoption of other emerging low-flashpoint fuels such as ammonia and hydrogen, thereby facilitating the industry's long-term decarbonization pathway.

Despite the comprehensive nature of this meta-analysis, certain limitations should be acknowledged. A notable geographic bias was observed, with 65% of the included studies originating from Europe and China. This regional concentration might limit the generalizability of some economic and operational findings to other parts of the world with different regulatory landscapes, fuel markets, and operational practices. Additionally, there were data gaps concerning smaller vessels (<5,000 DWT), as most studies focused on larger tankers, containerships, and ferries. Future research should aim to address these geographical and vessel-size biases to provide a more holistic understanding of LNG adoption.

Based on the findings of this meta-analysis, we propose the following recommendations: a.Continued research and development are crucial for improving the environmental per-formance of LNG. Specifically, efforts should focus on developing and commercializ-ing effective methane oxidation catalysts for existing engines to further reduce methane slip, thereby enhancing LNG's climate benefits. b.To accelerate the transition towards more sustainable maritime fuels, policymakers should consider mandating a minimum 20% bio-LNG blending by 2030. This would significantly reduce the carbon footprint of LNG while leveraging existing infrastruc-ture.

Given the critical role of human factors in safety, there is an urgent need for global standardization of IGF bunkering protocols and training programs. This would ensure consistent safety standards and reduce incident rates across the global fleet.

CONCLUSION

This meta-analysis comprehensively assessed the performance of Liquefied Natural Gas (LNG) as a marine fuel under the International Code of Safety for Ships Using Gases or Other Low- Flashpoint Fuels (IGF Code), focusing on emission reduction, economic viability, and safety performance. Our findings confirm that LNG delivers substantial and immediate benefits for air quality, primarily through significant reductions in sulfur oxides (SO_x) and particulate matter (PM). However, its contribution to global climate goals is more constrained, with a modest 12% net CO_2 equivalent (CO_2eq) reduction, largely due to the persistent challenge of methane slip. Thisunderscores the critical need for continued technological advancements in methane abatement and the prioritization of engine types with inherently lower methane emissions.

Economically, the adoption of LNG as a marine fuel presents a nuanced picture. While initial capital expenditure (CAPEX) is higher, the long-term operational expenditure (OPEX) savings can offset these costs, particularly for high-utilization vessels operating in Emission Control Areas (ECAs). The regional variations in economic viability highlight the importance of supportive policy frameworks and the development of robust bunkering infrastructure, especially in emerging maritime hubs. The IGF Code has proven to be an effective framework for managing the safety aspects of LNG operations. Our analysis demonstrates that the emphasis on comprehensive crew training is paramount for mitigating risks, as IGF-compliant training significantly reduces incident rates, particularly during critical bunkering operations.

In conclusion, LNG serves as a vital transitional fuel, offering immediate environmental advantages and a pathway towards decarbonization. However, its full potential for climate change mitigation hinges on addressing methane slip effectively. Future research should focus on exploring the scalability and economic feasibility of bio-LNG pathways, which offer significantly greater CO_2eq reductions, and further investigate the adaptability of the IGF framework to accommodate other carbon-neutral fuels as the maritime industry continues its journey towards a sustainable future.

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